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EFFECTS OF DECREASING TEMPERATURE AND ILLUMINATION INTENSITY ON SILICON SOLAR CELL PERFORMANCE

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February, 1970

E-5542

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ABSTRACT

Performance curves of nine silicon solar cells were obtained at simulated solar intensities of 136, 12.0, 4.6 and 2.7 mW/cm^2 at temperatures between 115 and 330° K. Efficiencies of the cells ranged from 9.1 to 15.6 percent under simulated Jupiter conditions (4.6 mW/cm^2, 140° K). Three cells showed poor performance caused by a Schottky (metal-semiconductor) barrier at the rear contact. Five other cells showed a flat spot on the I-V curves at low temperatures which is related to a drop in efficiency under Jupiter conditions.

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SUMMARY

Performance curves of nine 2x2 silicon solar cells were obtained at simulated solar intensities of 136, 12.0, 4.6 and 2.7 mW/cm^2 at temperatures between 115 and 330° K. Efficiencies of the cells ranged from 9.1 to 15.6 percent under simulated Jupiter conditions (4.6 mW/cm^2, 140° K).

Three cells showed an effect associated with a rectifying Schottky (metal-semiconductor) barrier at the rear contact. This effect is manifest as a curvature of the I-V curve near open circuit voltage and/or as a decrease in the open circuit voltage as the illumination intensity is increased.

A second effect that was observed on five other cells was an abrupt drop in efficiency as the temperature and intensity is decreased. The low temperature, I-V plots of these cells show the presence of a flat spot around the maximum power point. This effect significantly lowers cell efficiency under Jupiter conditions below that of cells not exhibiting this effect. The flat spot effect can be simulated with an analog circuit consisting of two solar cells in series, one having a 10 ohm shunt resistance.

INTRODUCTION

Previous studies (refs. 1-4) have indicated wide variability in the performance of silicon solar cells at low temperatures and illumination intensities. Although all cells were from current production runs and had similar, acceptable, room temperature performance (refs. 1-2) (~ 10 percent efficiency at 300° K, 136 mW/cm^2), many cells had unacceptable performance under conditions likely to be found at Jupiter (140° K, ~ 5 mW/cm^2). One cause for the poor performance at Jupiter was found to be high cell leakage (measured at 0.6 V reverse bias) (refs. 1-2). A simple test at room temperature consisting of the determination of the change in fill factor at two light intensities was devised to uncover these high leakage cells (ref. 2).

The purpose of the work described in this paper was to investigate further the performance of present-day silicon solar cells as a function of light intensity and temperature and to isolate additional causes of poor low temperature performance. The cells selected for this study were typical of cells being used on current satellites. The cells were from three manufacturers and were selected to have low leakages so the effects described in ref. 2 did not influence the low temperature performance. Light intensities ranged from 136 mW/cm^2 (AMO) to 2.7 mW/cm^2 and temperatures ranged between 115 and 330° K.

EXPERIMENTAL

Nine 2 cm x 2 cm silicon solar cells were measured in this study. They are typical of solar cells in current production and of those being supplied for spacecraft applications. They were obtained from three manufacturers (H-2 cells, C-4 cells and IP-3 cells) and all had silver-titanium contacts. Two cells (H103 and H115) had only two grid fingers; this modification was made in the hopes of improving low intensity performance. The rest of the cells had either 6 grid fingers (C) or 14 grid fingers (IP).

The apparatus and mounting technique was described in detail in ref. 2. A brief description of the test arrangement will be given here. The cells were mounted on a brass block using finger stock as shown in figure 1. This technique was the only one found to be suitable for cell measurement at these low temperatures. The holder was bolted to a cooled block located in a quartz-windowed vacuum chamber whose pressure was about 5×10^{-6} torr. The block temperature was controlled to ± 1° C at each temperature by control of the flow of liquid nitrogen through the block. Two copper-constantan thermocouples mounted beneath the cells monitored the temperature.

The cells were irradiated with light from a filtered xenon light source whose spectral distribution approximated outer space sunlight. The intensity at the test plane was set at air mass zero conditions (136 mW/cm^2) with a standard silicon solar cell calibrated for outer space conditions using a high altitude airplane (ref. 5). Uniformity at the

test plane was ± 1 percent. Neutral density screens were used to lower the intensity from 136 mW/cm^2 to 12.0, 4.6 and 2.7 mW/cm^2.

The current-voltage (I-V) characteristics of the cells were measured with an electronic load and an x-y plotter. The inaccuracy of the data is thought to be less than ± 3 percent for voltage and current and ± 4 percent for efficiencies (ref. 2). At low temperatures and high light intensities some cell warming above block temperature was noted. This was determined by following the open circuit voltage (V_{OC}) of the cell immediately after the cell was illuminated. The change in voltage (averaging 14 mV) was then added to the equilibrium I-V curve to obtain the performance of the cell at the temperature of the block. The precision of the measurements was checked by remounting some cells and repeating the measurement. The results were within the accuracies stated previously.

If the contact between the cell and the block is somewhat resistive, the measured voltage will be lowered, especially at high currents. This effect appears as a high series resistance in the I-V curve, which leads to a loss in maximum power. One cell measured in this work showed such a loss in power at high intensities (cf. cell IP7, fig. 4a), although the data at low intensities are unaffected. An independent contact to the rear of the cell for measuring voltage would eliminate this problem.

RESULTS

Figure 2 shows a log-log plot of the short circuit current of a typical cell versus illumination intensity. As expected, the curve is

linear and has a slope equal to one. This result confirms the accuracy of the quoted intensities.

Figures 3a-d through 11a-d show the performance curves of the silicon cells in this study as a function of temperature and illumination intensity. For convenience, open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), and efficiency (Eff) are plotted together for each intensity. The general features of the curves are quite similar for all the cells — with decreasing temperature the open circuit voltage increases, the short circuit current decreases, and the efficiency tends to level off or peak. The detailed, specific differences of interest will be discussed subsequently.

Three cells (C191, C214, and H115) were run a second time (as indicated by the solid data points) with generally excellent agreement between the runs. These cells were remounted and remeasured because their initial performance or I-V curves had shown several unusual features. Table 1 lists Jupiter condition efficiencies as well as a tabulation of peculiarities of the cell I-V curves with variations in the performance curves for the cells in this study. The efficiencies of the cells under Jupiter conditions (4.6 mW/cm^2 140° K) ranged from 9.1 (C206) to 15.6 percent (C191).

Three cells (C191, C214, and IP6) showed the effects of a rectifying rear contact. In the initial tests, cells C191 and C214 showed a nonlinearity in the V_{OC} versus temperature curve for an intensity of 136 mW/cm^2 at temperatures below 220° K. Remounting largely eliminated this nonlinearity for cell C191 (fig. 7a), but not for cell C214. However, the open circuit voltage of cell C191 at 116° K and 136 mW/cm^2 was lower in both runs

than the V_{OC} at 12 mW/cm^2, contrary to what would be expected theoretically for a photovoltaic cell. The I-V curves for the two light levels are shown in figure 12. Cell C214 also showed this reversal of V_{OC} with intensity but to a greater degree than C191 as shown in figure 13.

Furthermore, the I-V curve for cell C214 taken at 12 mW/cm^2 showed a distinct positive curvature near the open circuit condition. This type of behavior would be expected of a Schottky (metal-semiconductor) barrier at the rear contact. This barrier would form a photovoltaic diode of opposite polarity to the solar cell junction and would therefore act to produce a bucking voltage which is dependent upon the illumination intensity. At higher light levels the voltage of the bucking diode would be higher thus leading to a decrease in the observed voltage with increasing light intensity.

A slight positive curvature near V_{OC} was also observed with cell IP6 . The V_{OC} versus temperature curve for cell IP6, however, was linear and no voltage reversal was observed.

Another unusual effect was noted on cell H115. This cell showed a sharp peak in cell efficiency at about 200° K and low intensity, e.g., figures 11c and d, which was confirmed in a second run. The I-V curve of this cell showed a definite flat spot around the maximum power region of the curve at lower intensities at temperatures below 200° K. A typical curve is shown in figure 14. This flat spot was observed in five (IP101, C112, C206, H103, and H115) of the nine cells tested. This effect appears to be a major problem for silicon cells operating under Jupiter conditions.

The average efficiency at Jupiter of the five cells showing the flat spot is 11.6 percent whereas the average efficiency of the remaining cells is 15.0 percent.

Of the five cells that showed the flat spot in the I-V curve, four of them (C112, C206, H103, and H115) exhibited a noticeable departure from linearity in the short circuit current versus temperature plots. A drop in current for these cells generally coincided with the drop in efficiency below 220° K. This change in current was apparent at all intensity levels. In the remaining cell that showed the flat spot (IP101), the drop in current may not be of sufficient magnitude to be observed (cf. fig. 5a and b and 5c and d). It can also be seen from Table 1 that cell C214 also showed the drop in short circuit current with temperature (figs. 9a-d) although no flat spot was observable in the I-V curve (fig. 13). It is possible that the flat spot could be obscured by the Schottky barrier on the rear contact.

The flat spot phenomenon appears widespread as both the I-V and the performance curves presented by other authors (refs. 2-4) show similar peculiarities. The origin of this problem is not clear. To simulate this effect, analog circuit simulation was attempted. Figure 15 shows the I-V curve obtained from an analog circuit consisting of two silicon solar cells connected in series, one having a low shunt resistance of about 10 ohms. Both cells were illuminated at about an AM1 intensity. The flat spot in the I-V curve looks very much like that obtained experimentally on the five test cells. It is not clear, however, that this simulation provides a useful model for the analysis of the flat spot phenomena in the cells

because it is not likely that the cell contains two photovoltaic junctions connected in series with both junctions forward. A more likely model may be that of a Schottky barrier in parallel with the p-n junction of the solar cell (ref. 6). This condition could be obtained if the top contact shorted through the barrier in some manner.

SUMMARY OF RESULTS

Performance curves of nine silicon solar cells were obtained at simulated solar intensities of 136, 12.0, 4.6 and 2.7 mW/cm^2 and at temperatures between 115 and 330° K. The efficiencies of the cells ranged from 9.1 to 15.6 percent under simulated Jupiter conditions (4.6 mW/cm^2, 140° K).

Three cells showed an effect associated with a rectifying Schottky (metal-semiconductor) barrier at the rear contact. Such a barrier acts as a diode opposed to the solar cell junction diode. This effect is manifest as a curvature of the I-V curve near open circuit voltage and/or as a decrease in the open circuit voltage as the illumination intensity is increased.

A second effect that was observed on five other cells was an abrupt drop in efficiency as the temperature is decreased. Also apparent in these cells is a flat spot in the I-V curve around the maximum power point at the low temperatures and intensities. This effect significantly lowers the cell efficiency under Jupiter conditions below that of cells not exhibiting this effect. It therefore appears to be a major problem.

The flat spot effect could be simulated by an analog circuit consisting of two solar cells in series, one having a low shunt resistance, the other a normal high shunt resistance.

REFERENCES

1. Liebert, Curt H.: Solar Cell Performance at Jupiter Temperature and Solar Intensity. Presented at Seventh IEEE Photovoltaic Specialists Conference, Pasadena, Calif., Nov. 19-21, 1968.
2. Liebert, Curt H.; and Hart, Russell E., Jr.: Solar-Cell Performance at Low Temperatures and Simulated Solar Intensities. NASA TN D-5547, 1969.
3. Lambert, Robert J.: Characteristics of Solar Cells at Low Temperatures. Conference Record of the Seventh Photovoltaic Specialists Conference. IEEE, 1968, pp. 97-100.
4. Ralph, Eugene L.: Performance of Very Thin Silicon Solar Cells. Conference Record of the Sixth Photovoltaic Specialists Conference. Vol. 1. IEEE, 1967, pp. 98-116.
5. Brandhorst, Henry W., Jr.; and Boyer, Earle O.: Calibration of Solar Cells Using High-Altitude Aircraft. NASA TN D-2508, 1965.
6. Zettler, R. A.; and Cowley, A. M.: ρ-n Junction-Schottky Barrier Hybrid Diode. IEEE Trans. on Electron Devices, vol. ED-16, no. 1, Jan. 1969, pp. 58-63.

TABLE 1 - Comparisons Between Performance Curves and Current-Voltage Curves at Low Temperatures

Cell Number	Efficiency under Jupiter conditions (140°K, 4.6 mw/cm^2)	Performance Curves			Current-Voltage Curves		
		Drop in V_{OC} as temperature decreases	Drop in I_{SC} as temperature decreases	Drop in P_{MAX} as temperature decreases	Flat spot around P_{MAX}	High series resistance	V_{OC} decreasing with increasing intensity or a curvature near V_{OC}
IP6	15.3					√	√
IP7	15.0			√		√	
IP101	14.8			√	√		
C112	14.4		√	√	√		
C191	15.6						√
C206	9.1	√	√	√	√		
C214	14.0	√	√	√		√	√
H103	10.3		√	√	√		
H115	9.6		√	√	√		

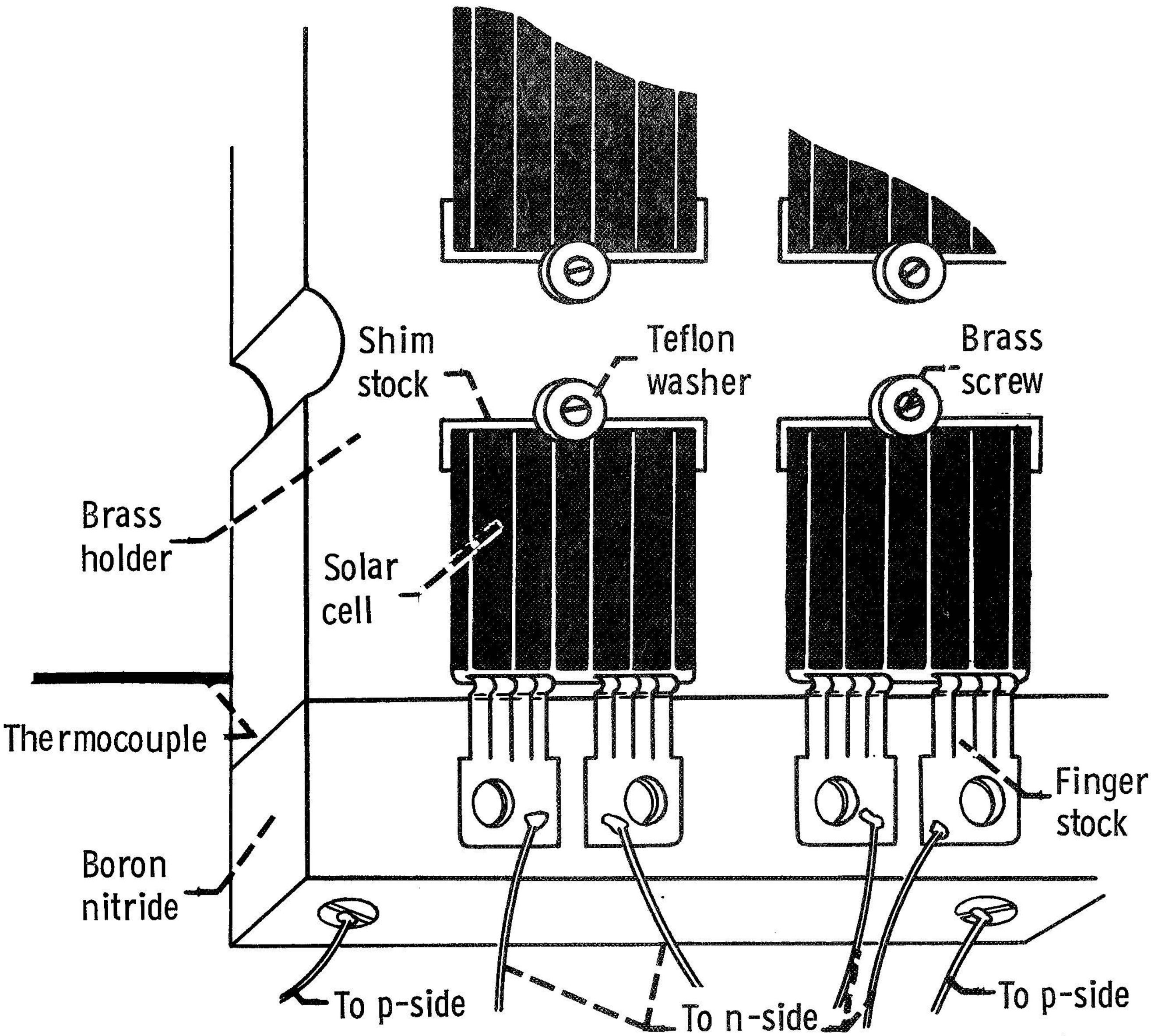

Figure 1. - Mounting of n-p silicon solar cells to holder.

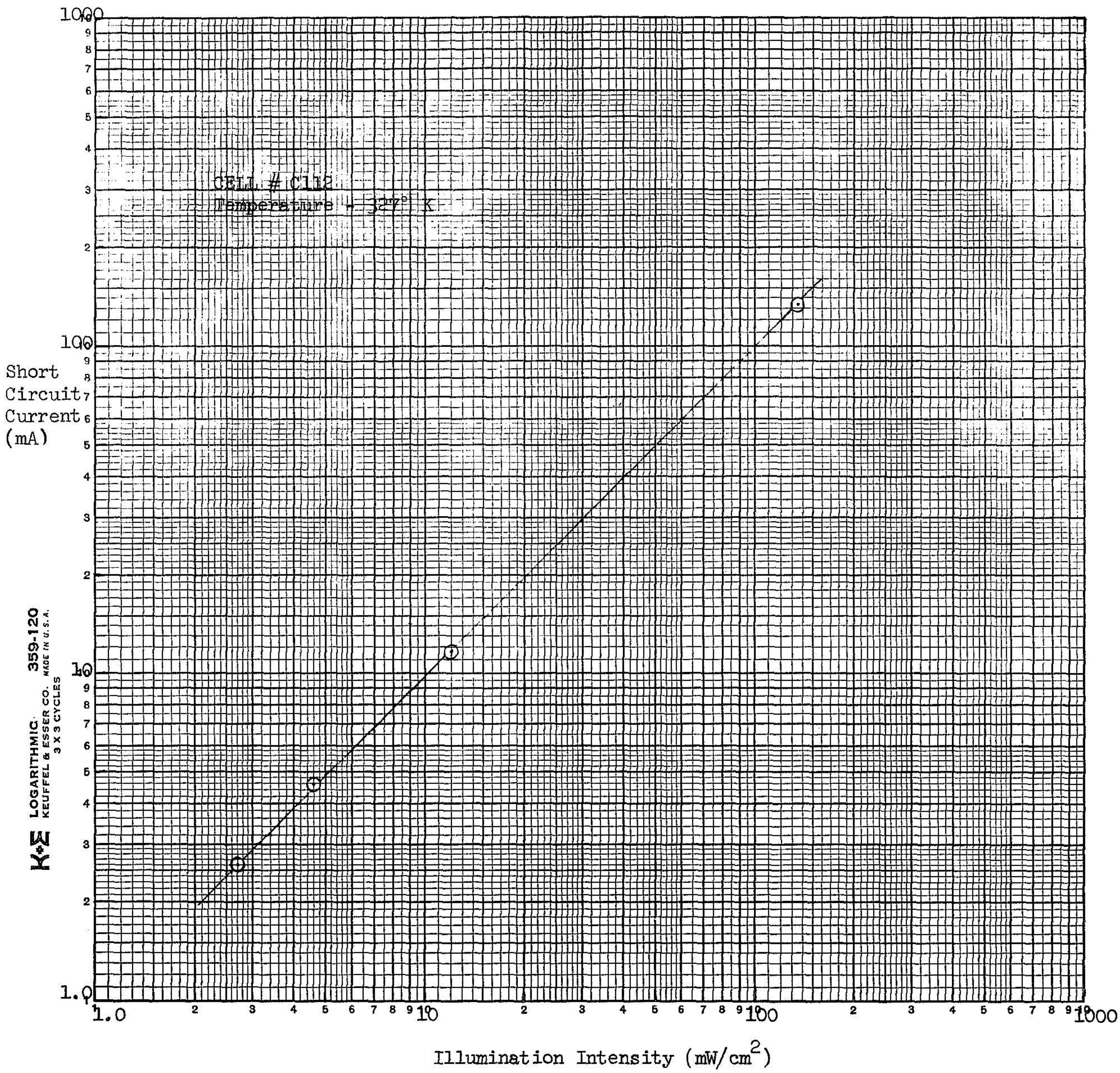

Figure 2 - Relationship between a solar cell short circuit current and illumination intensity.

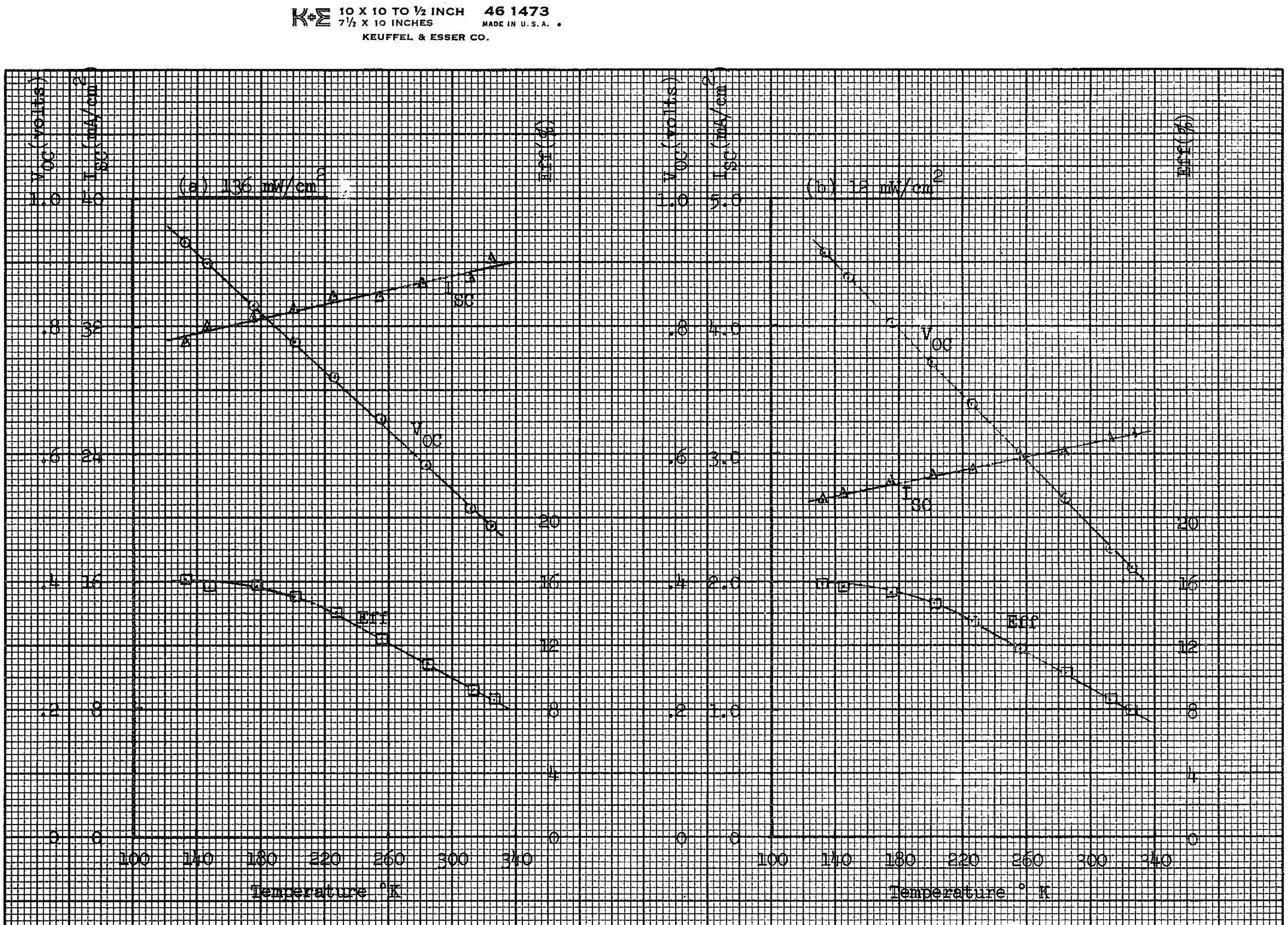

Figure 3(a) & (b) - Performance curves of cell IP6 as a function of temperature at 136 and 12 mW/cm^2.

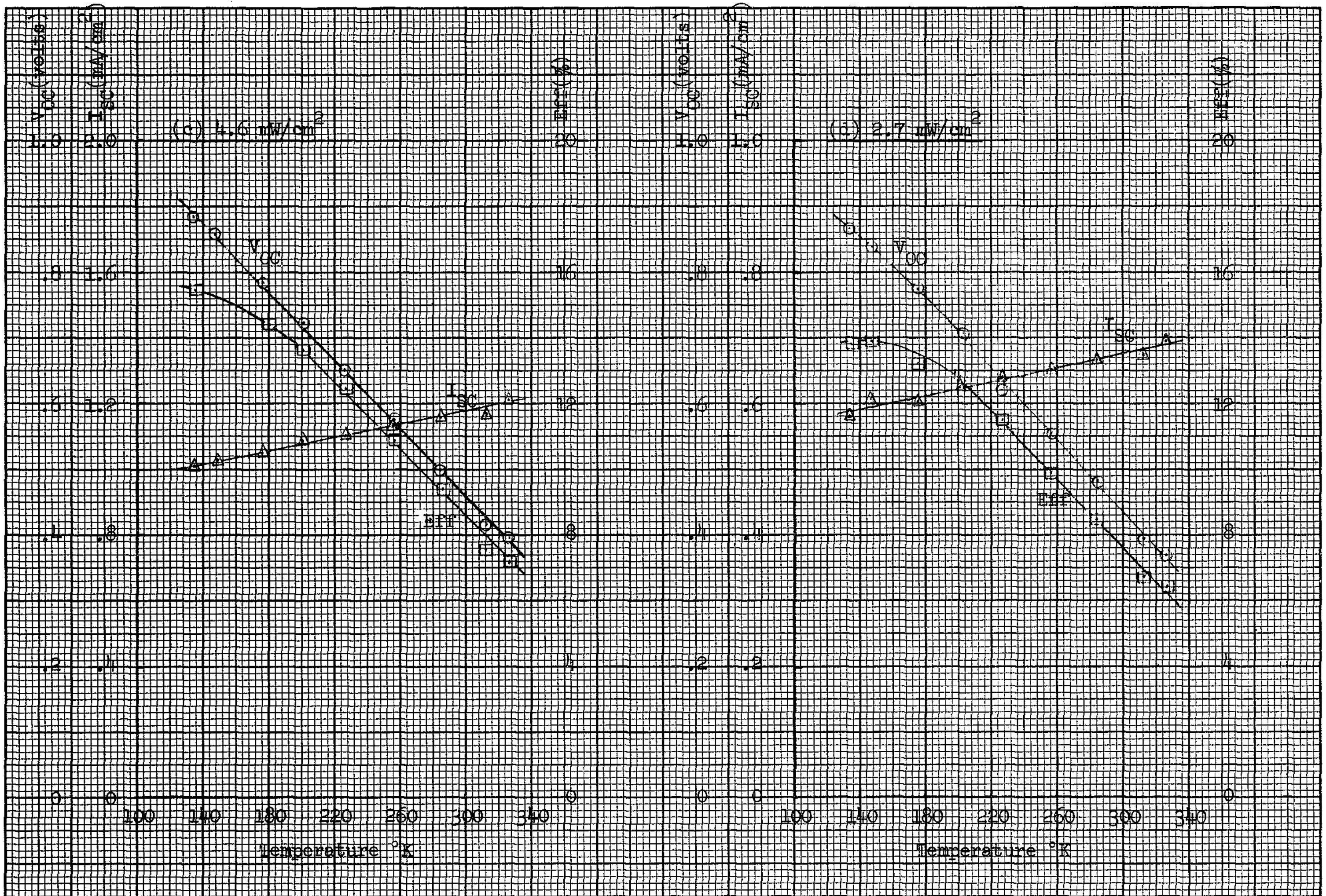

Figure 3(c) & (d) - Performance curves of cell IP6 as a function of temperature at 4.6 and 2.7 mW/cm^2.

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7½ X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

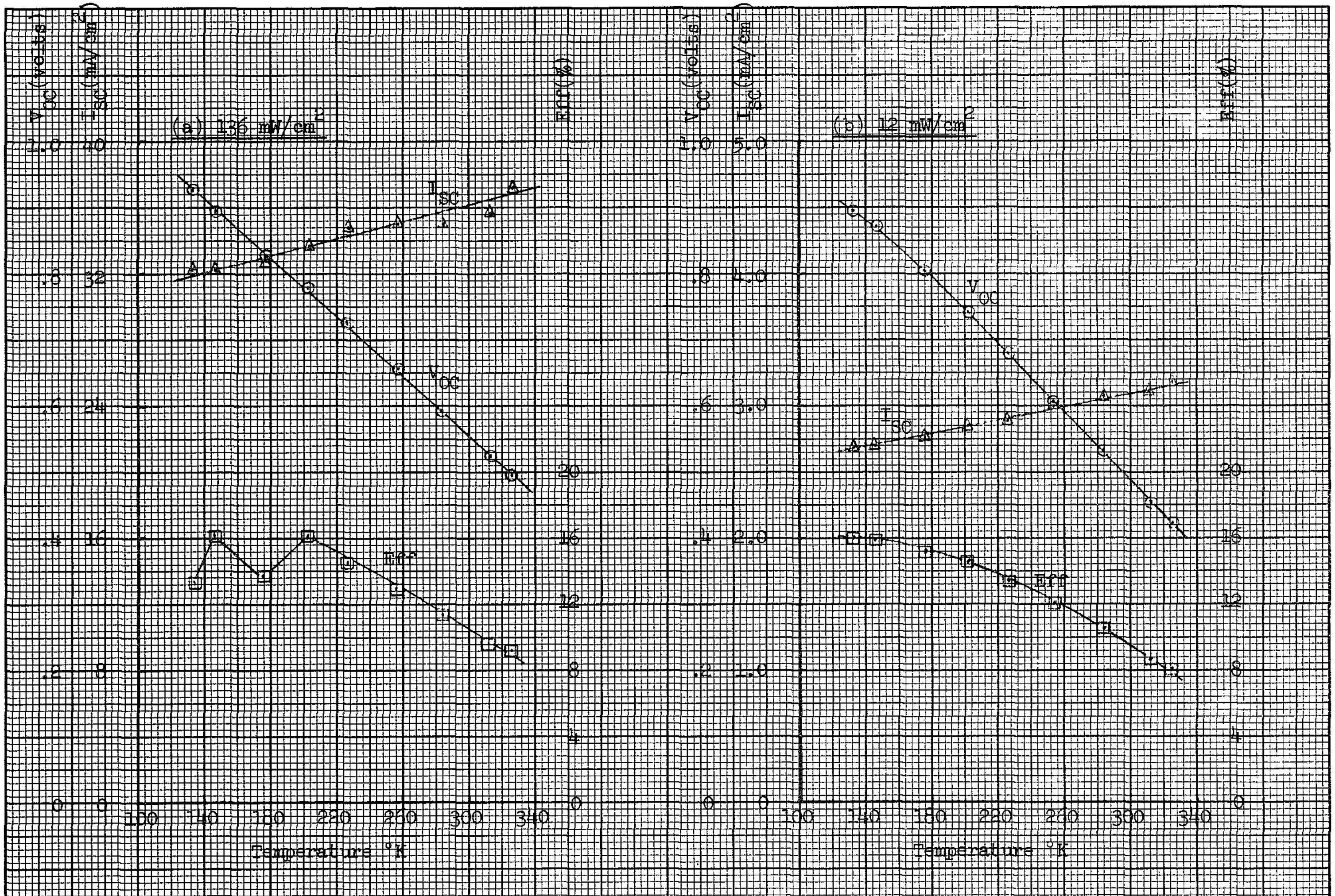

Figure 4(a) & (b) - Performance curves of cell IP7 as a function of temperature at 136 and 12 mW/cm^2.

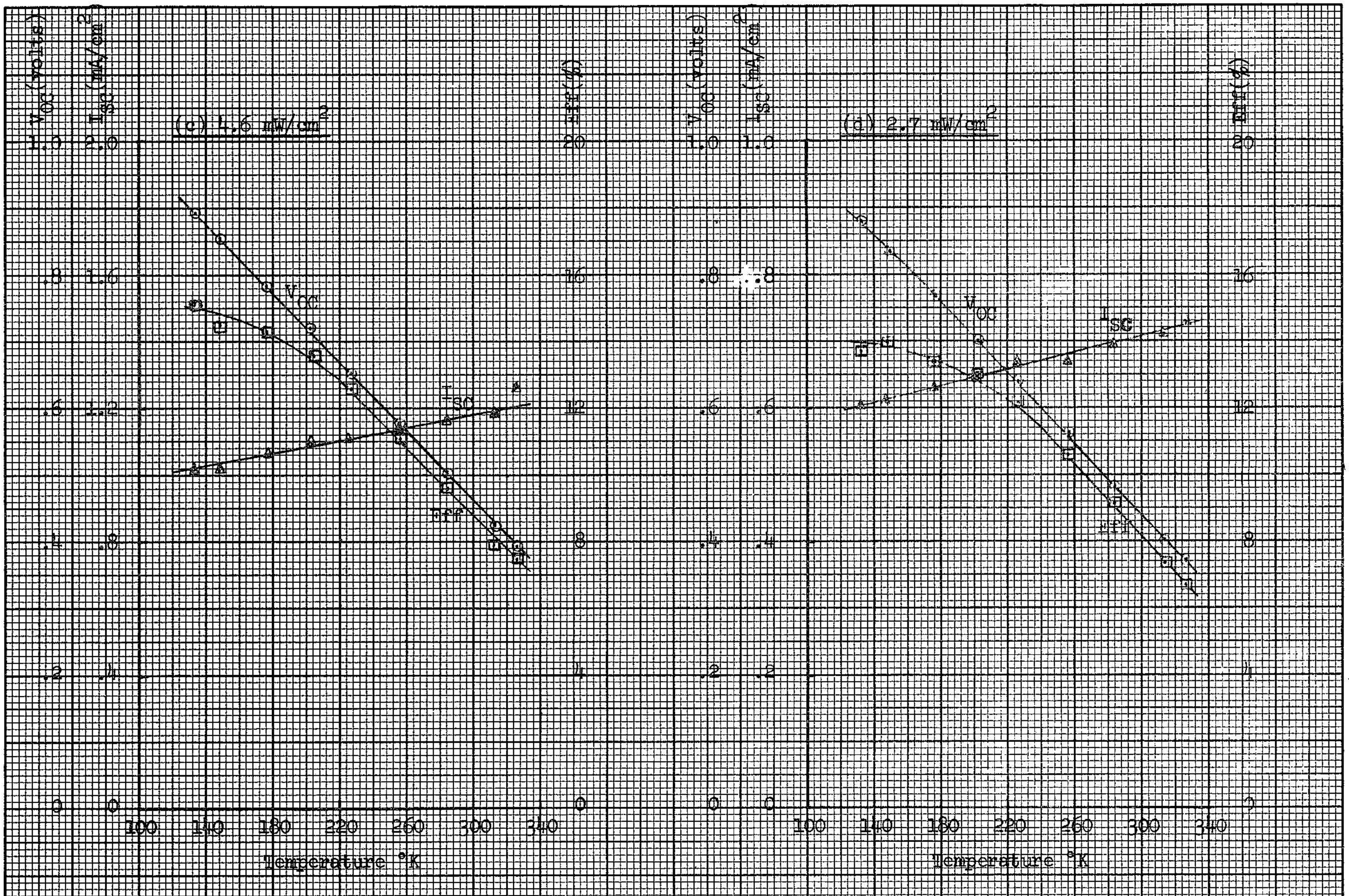

Figure 4(c) & (d) - Performance curves of cell IP7 as a function of temperature at 4.6 and 2.7 mW/cm^2.

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7½ X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

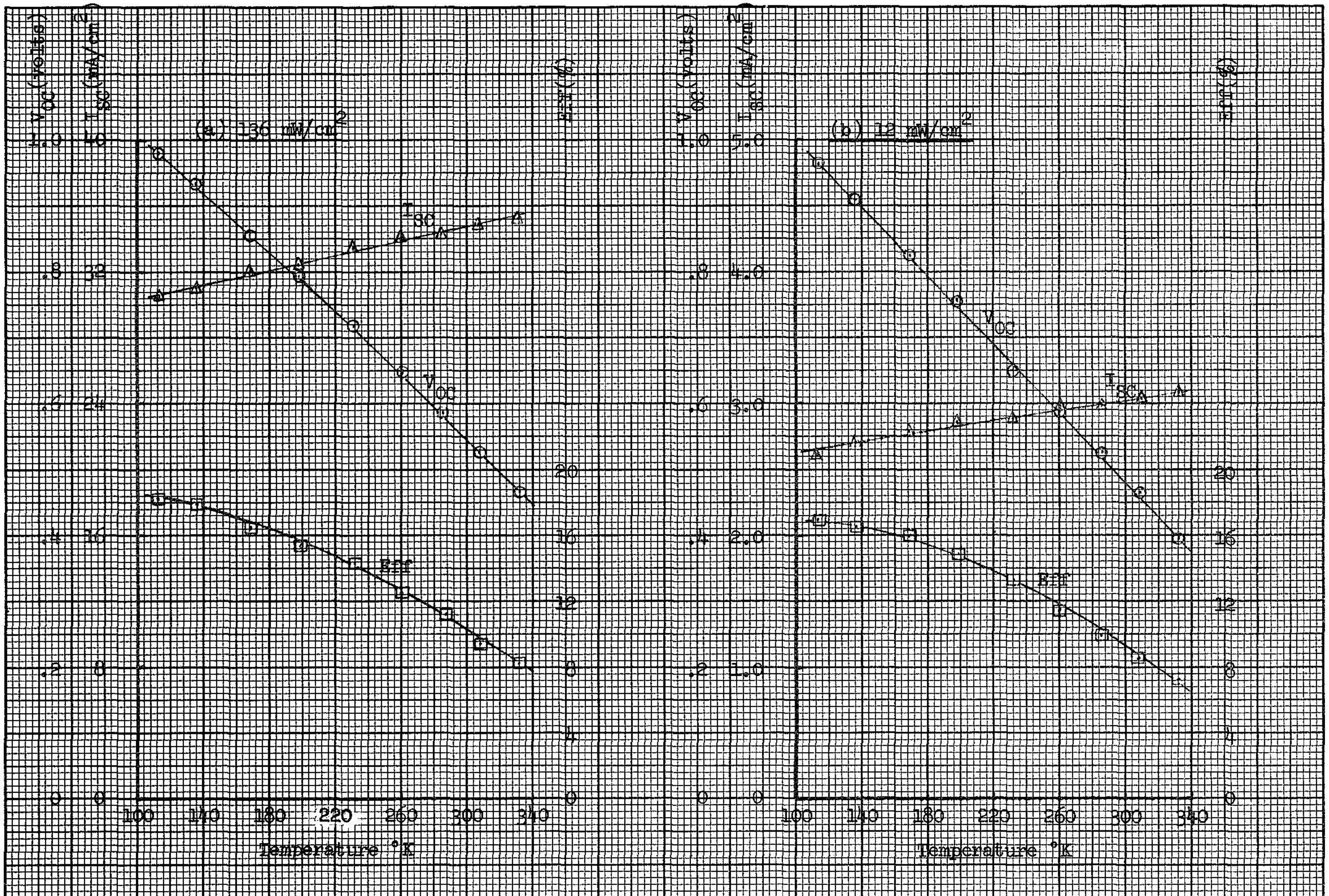

Figure 5(a) & (b) - Performance curves of cell IP101 as a function of temperature at 136 and 12 mW/cm^2.

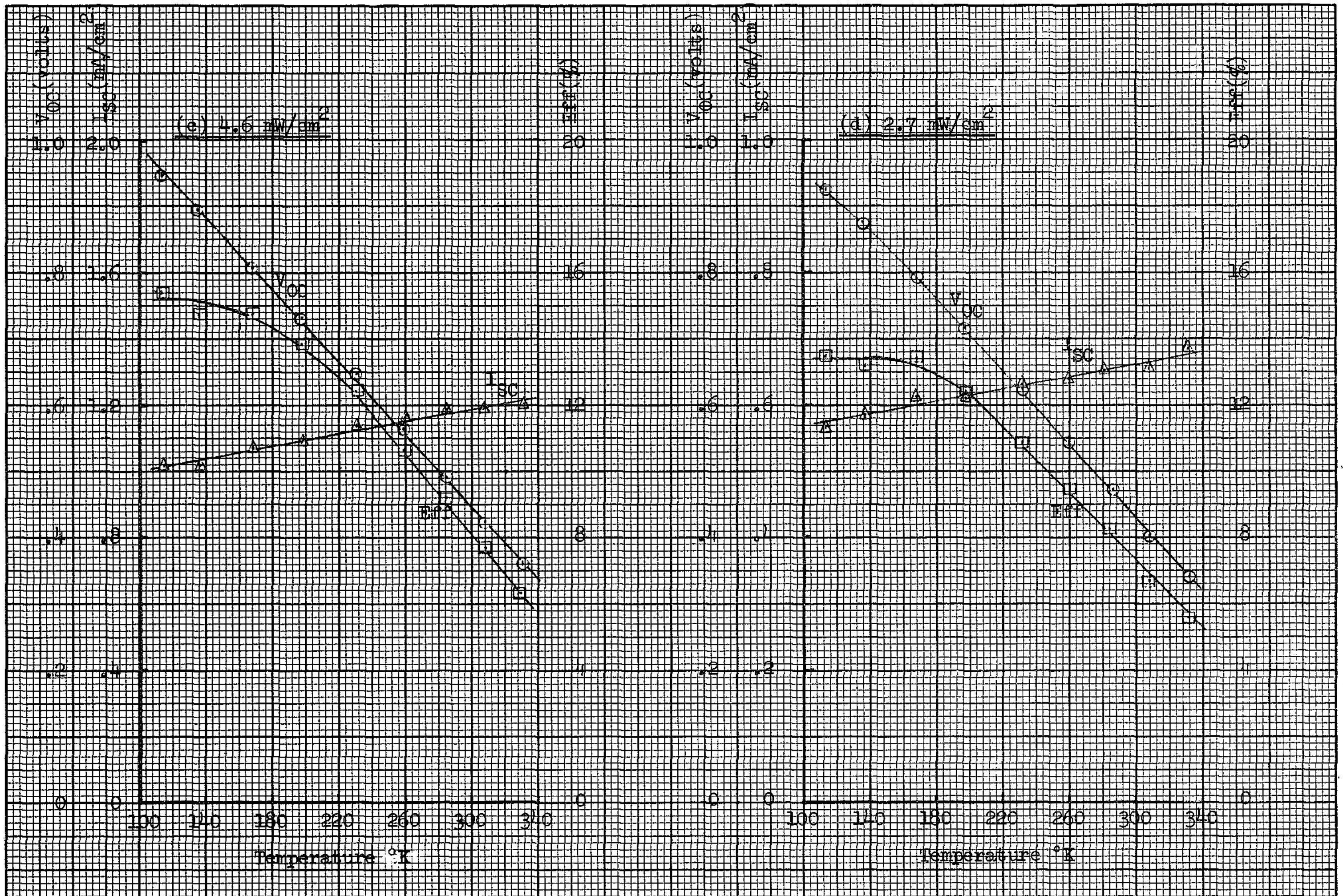

Figure 5(c) & (d) - Performance curves of cell IP101 as a function of temperature at 4.6 and 2.7 mW/cm^2.

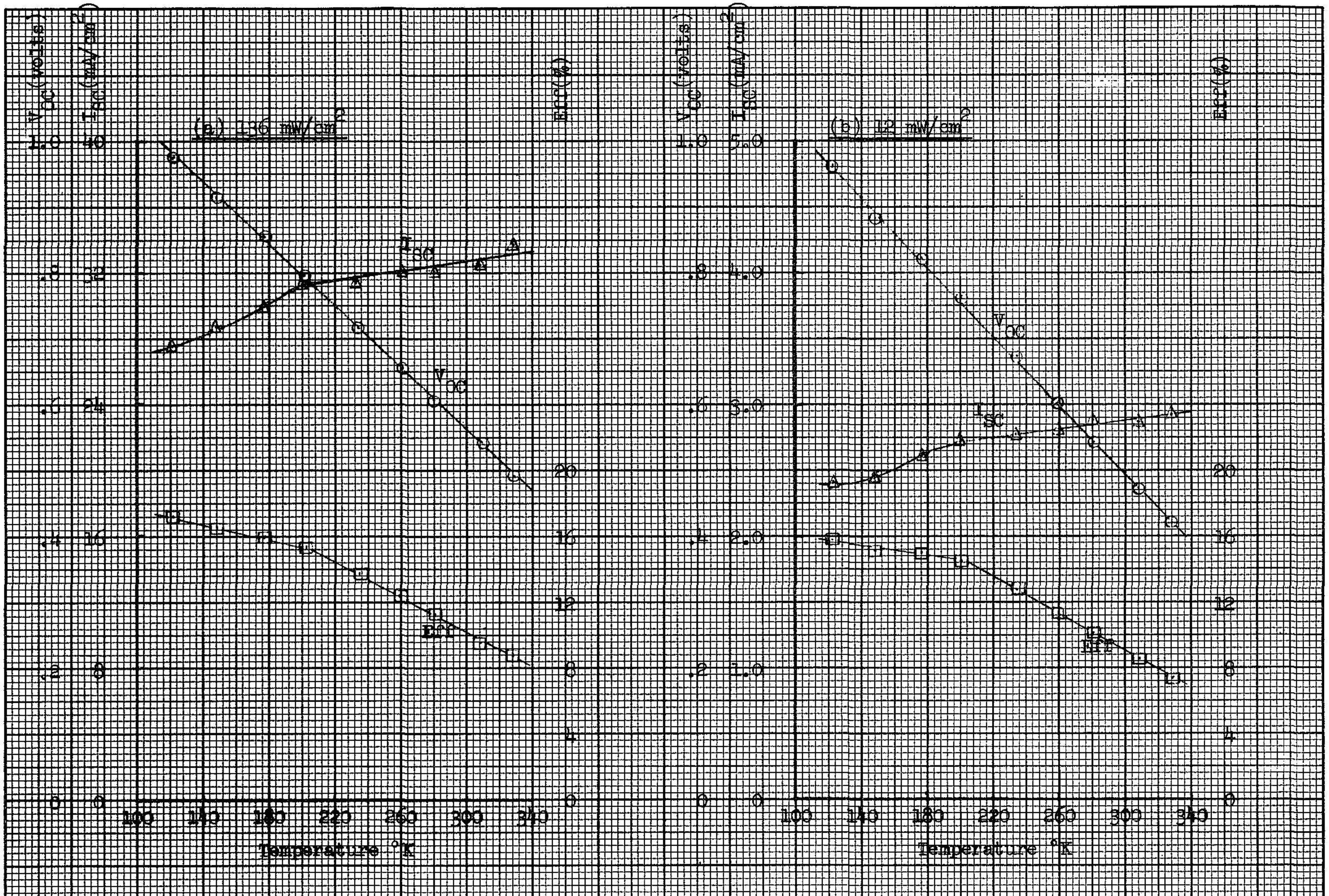

Figure 6(a) & (b) - Performance curves of cell C112 as a function of temperature at 136 and 12 mW/cm^2.

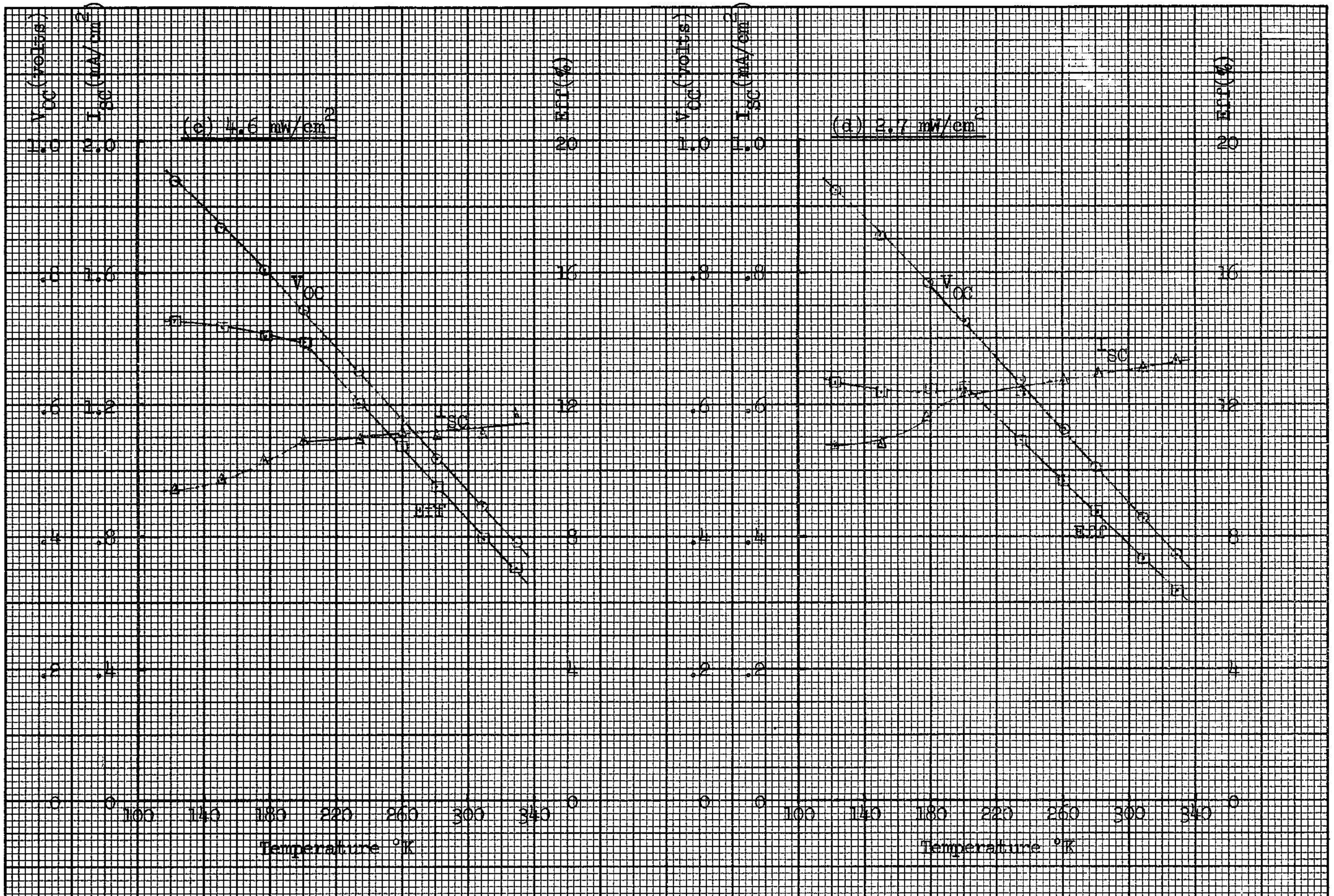

Figure 6(c) & (d) - Performance curves of cell C112 as a function of temperature at 4.6 and 2.7 mW/cm^2.

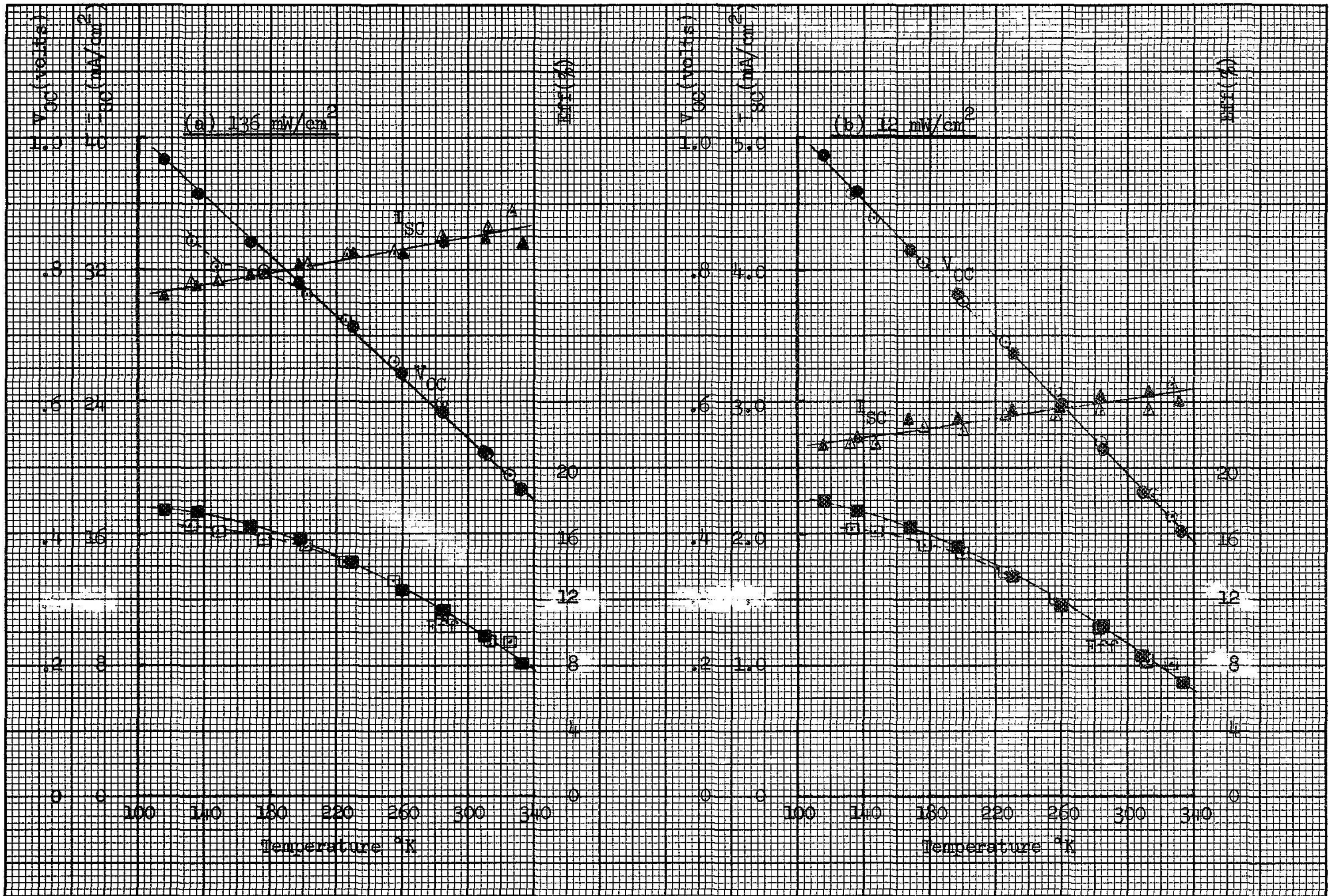

Figure 7(a) & (b) - Performance curves of cell C191 as a function of temperature at 136 and 12 mW/cm². Solid data points measured after remounting of cells.

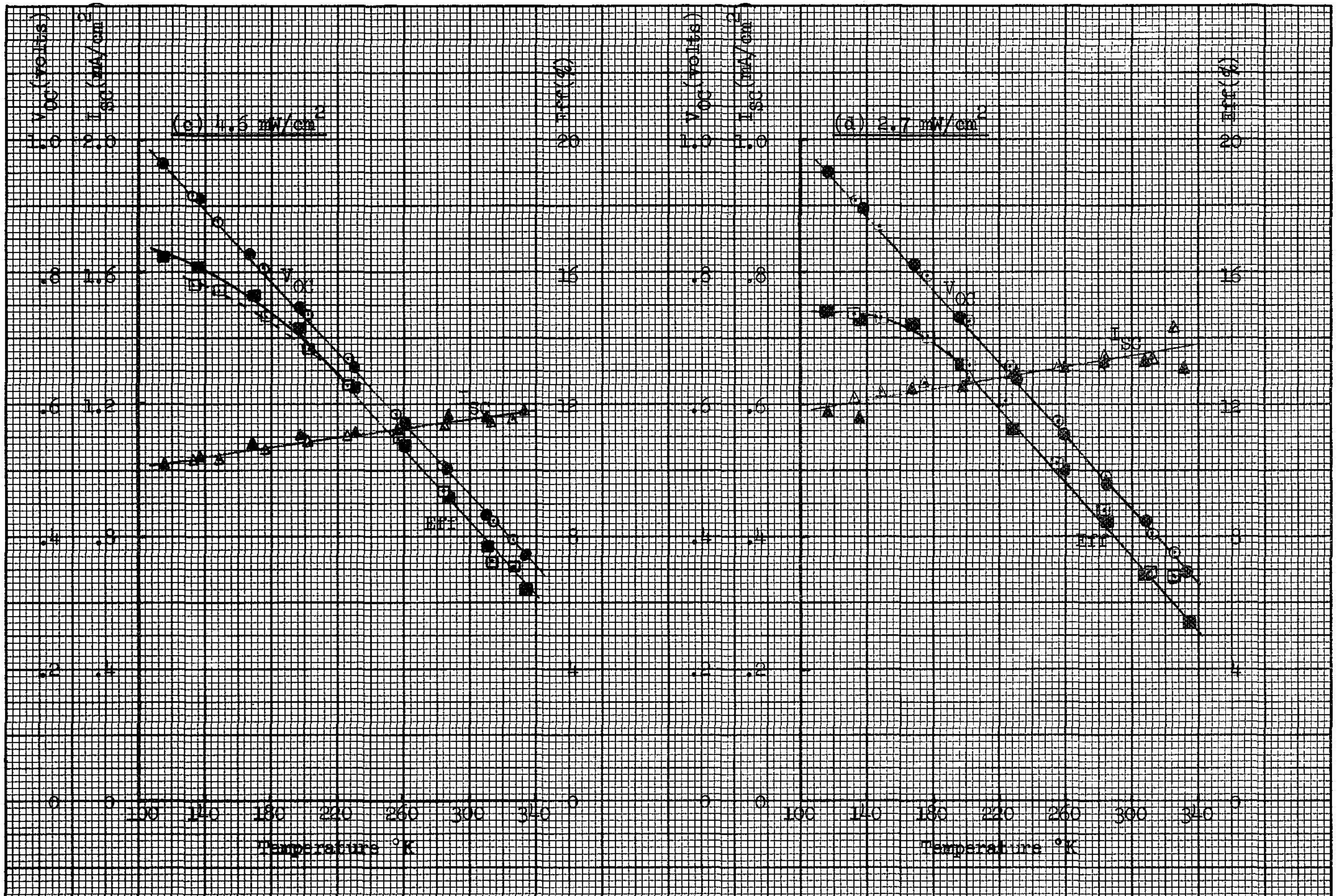

Figure 7(c) & (d) - Performance curves of cell C191 as a function of temperature at 4.6 and 2.7 mW/cm^2. Solid data points measured after remounting of cells.

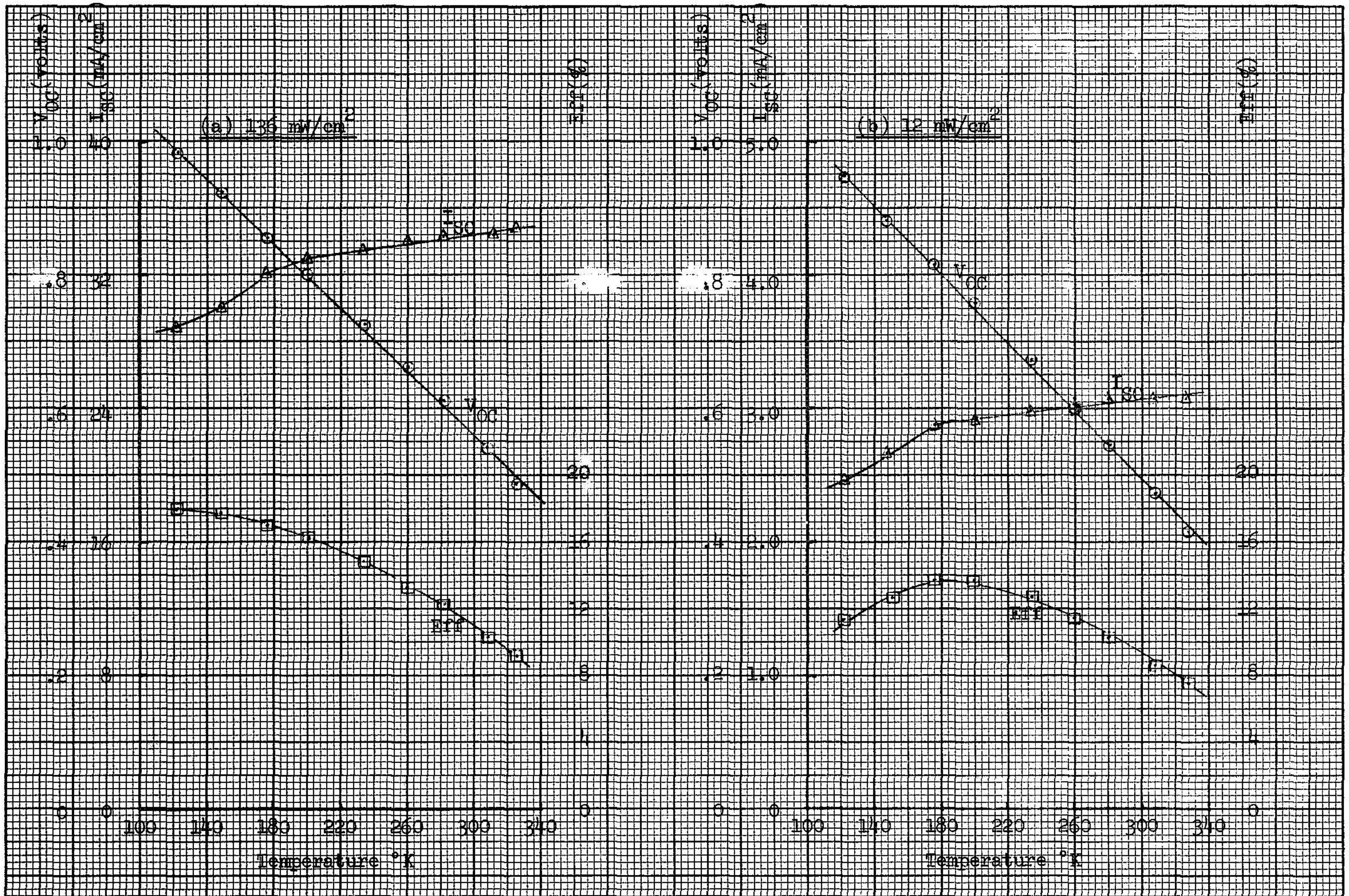

Figure 8(a) & (b) - Performance curves of cell C206 as a function of temperature at 136 and 12 mW/cm².

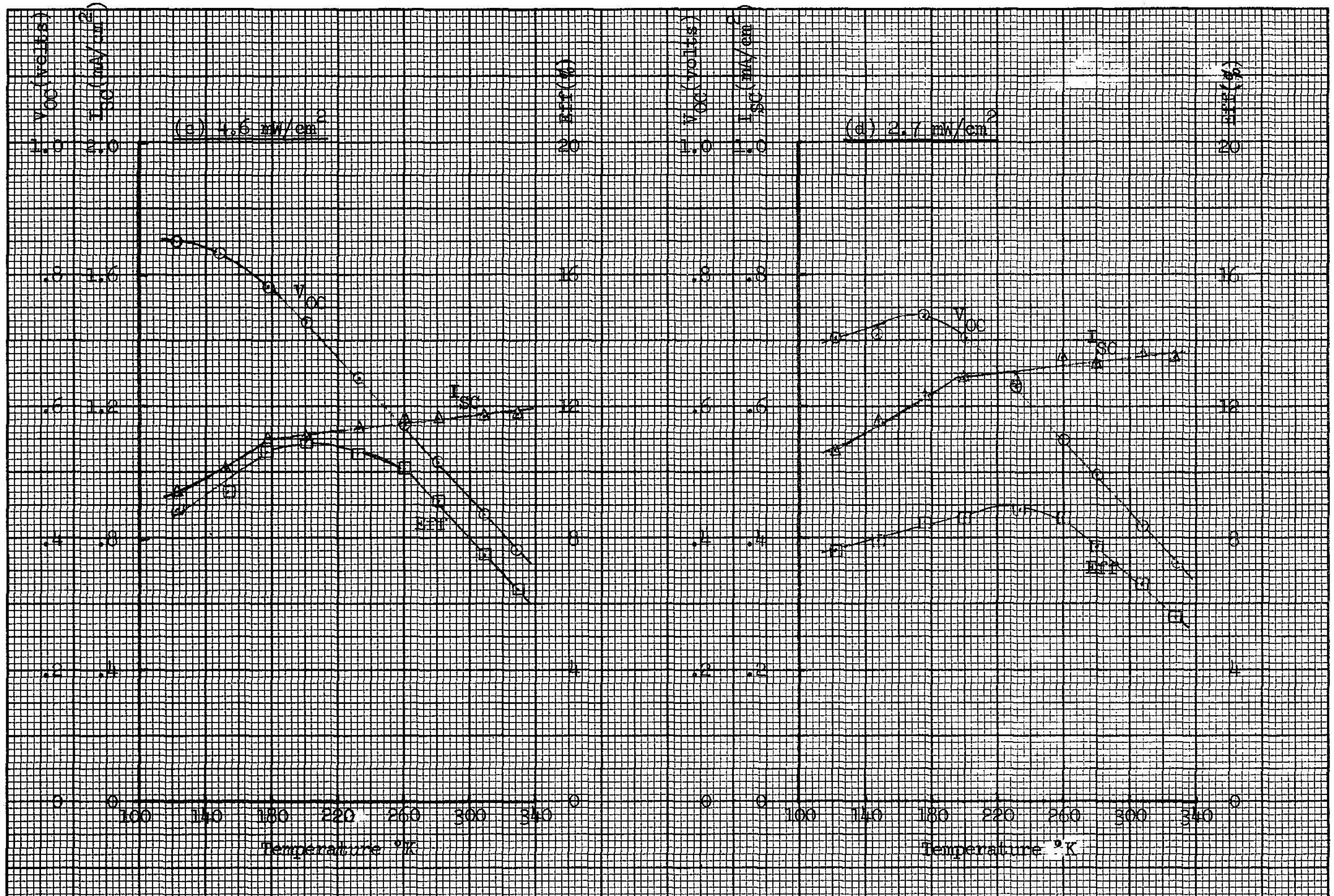

Figure 8(c) & (d) - Performance curves of cell C206 as a function of temperature at 4.6 and 2.7 mW/cm^2.

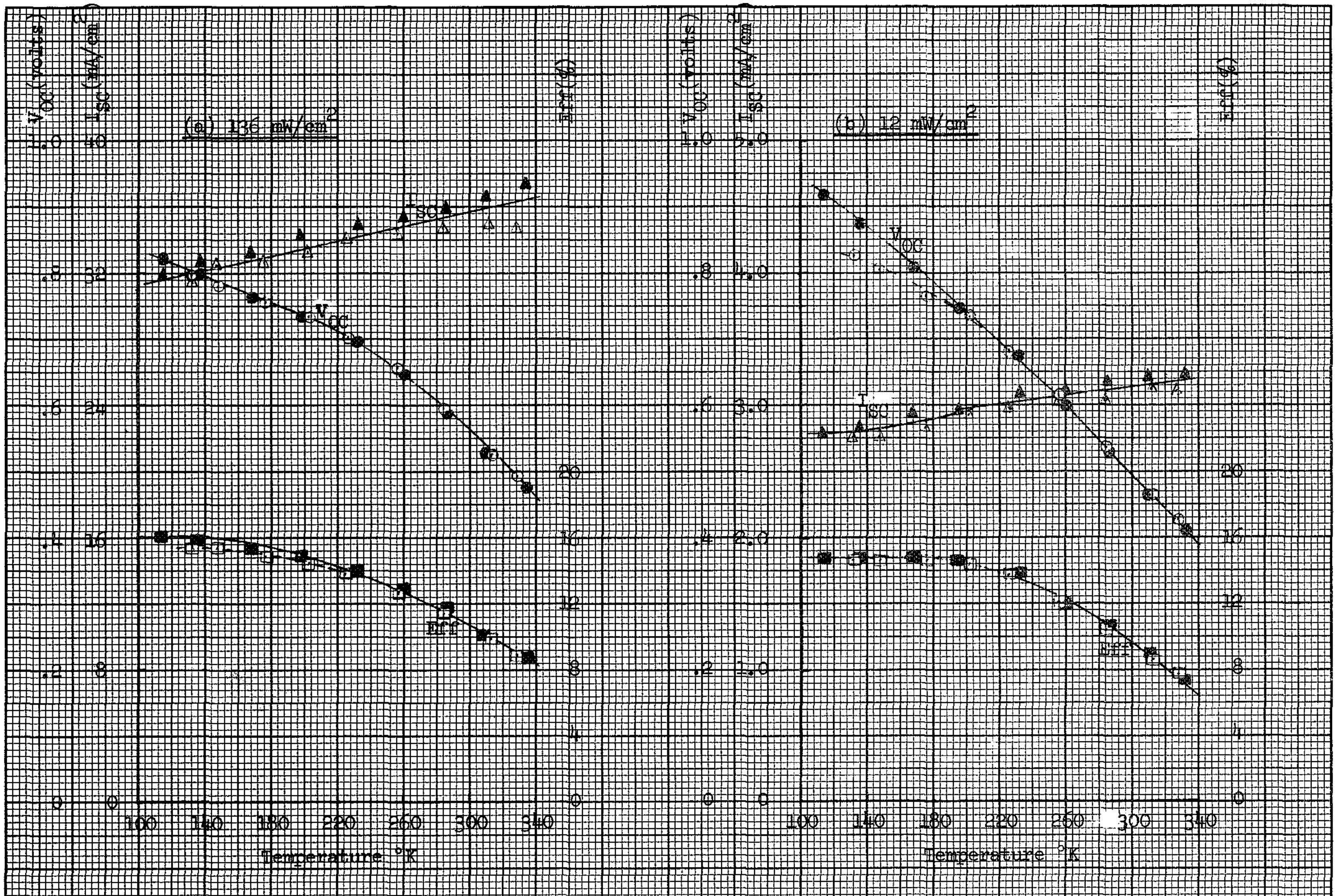

Figure 9(a) & (b) - Performance curves of cell C214 as a function of temperature at 136 and 12 mW/cm². Solid data points measured after remounting of cells.

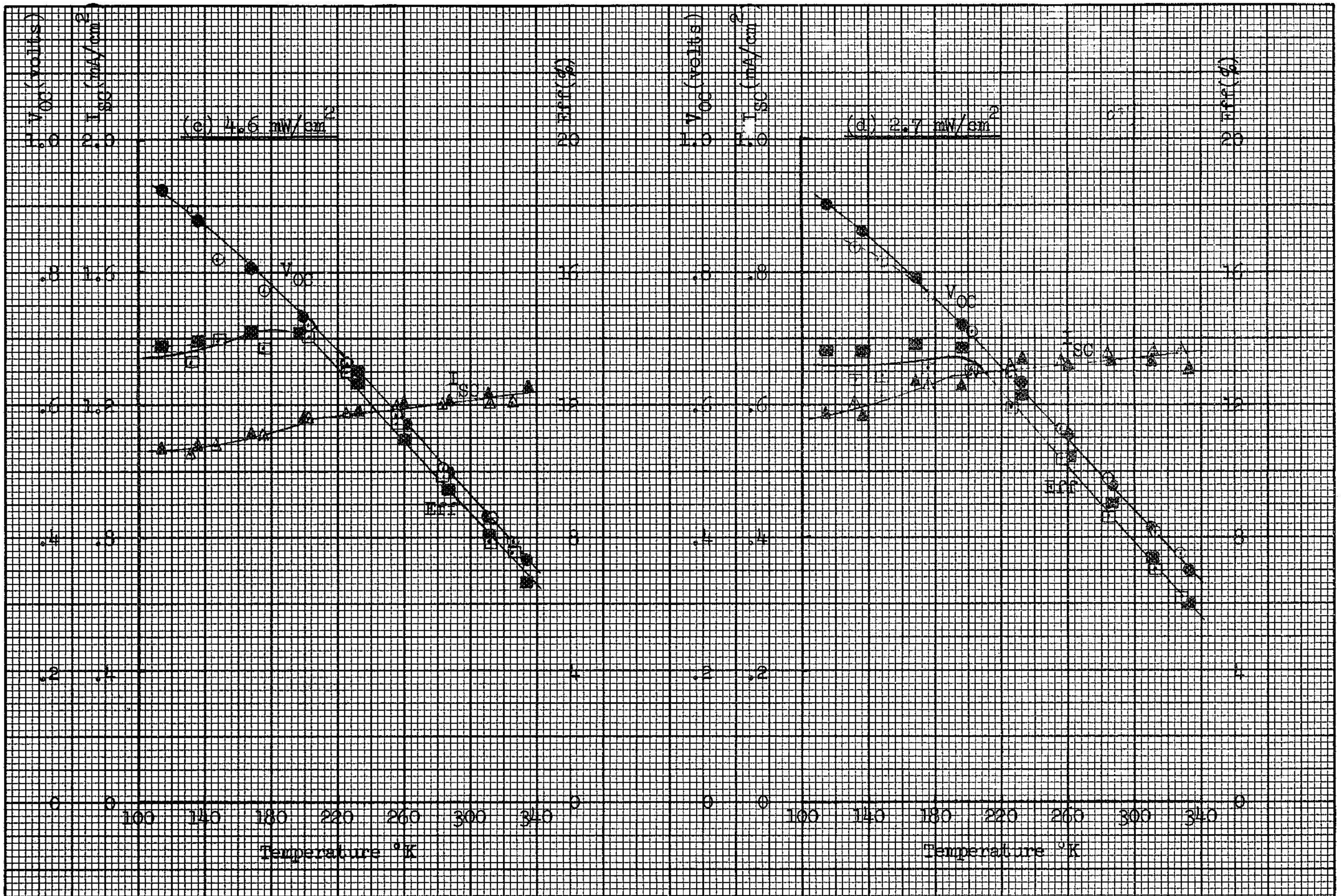

Figure 9(c) & (d) - Performance curves of cell C214 as a function of temperature at 4.6 and 2.7 mW/cm^2. Solid data points measured after remounting of cells.

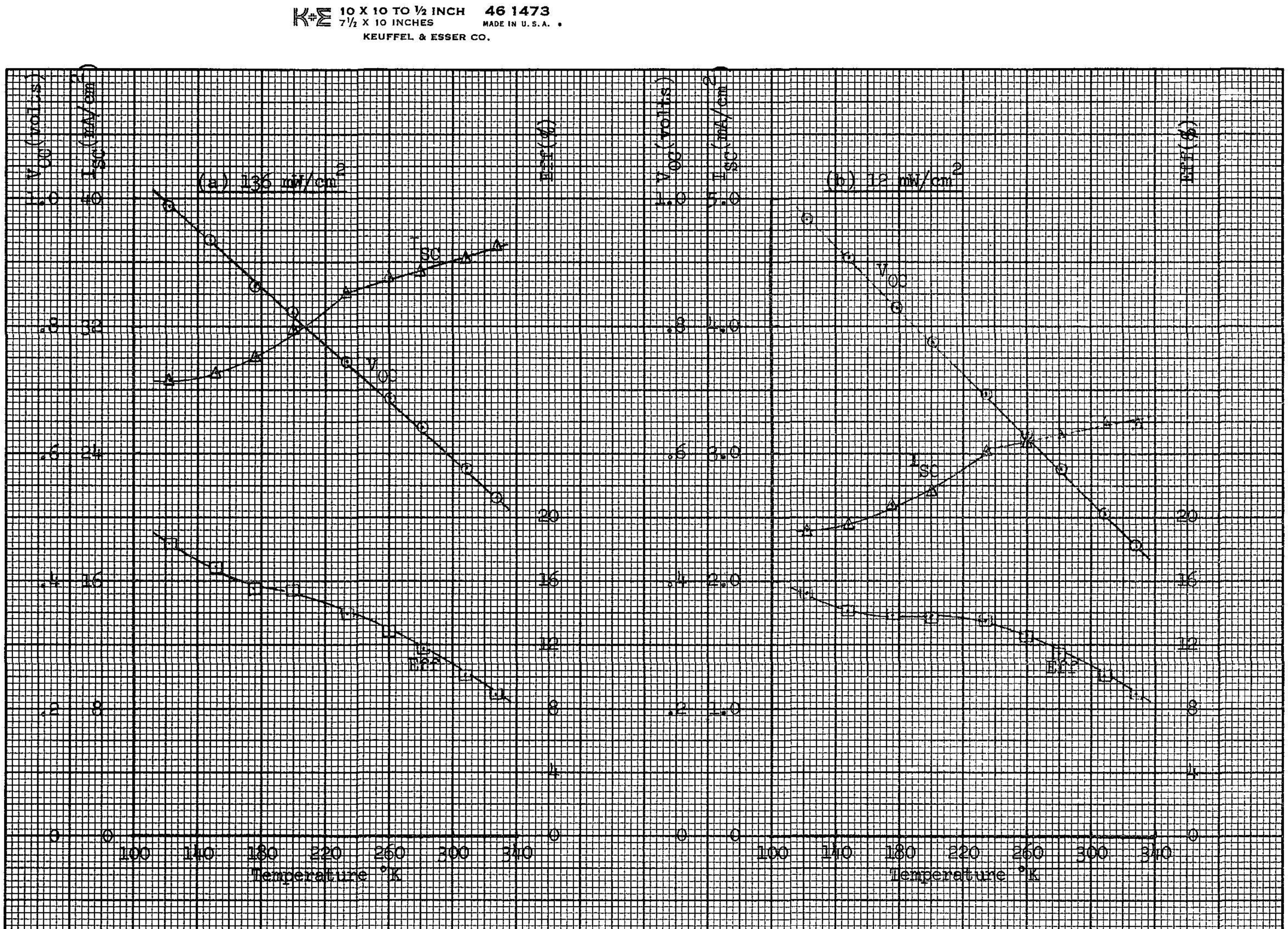

Figure 10(a) & (b) - Performance curves of cell H103 as a function of temperature at 136 and 12 mW/cm^2.

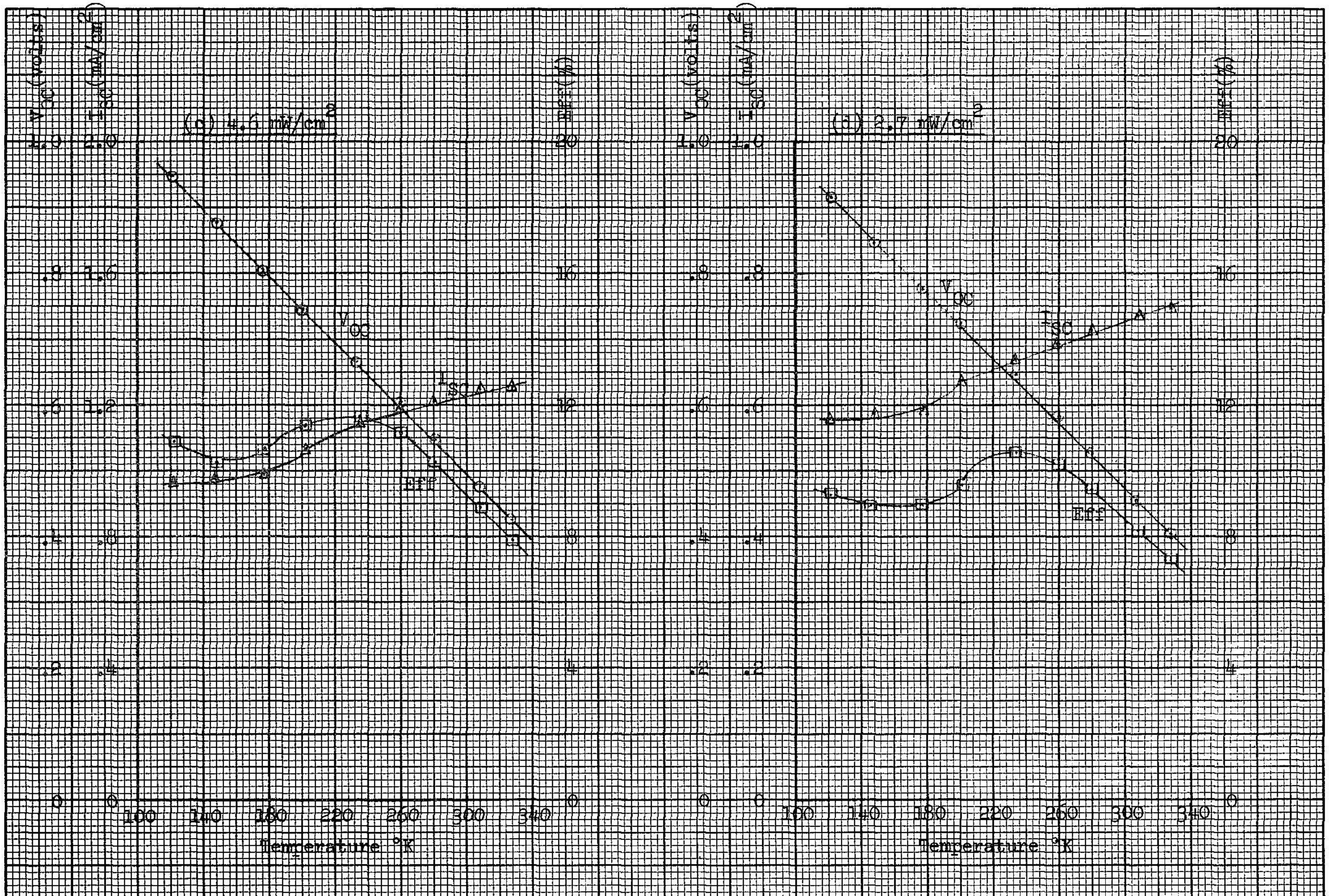

Figure 10(c) & (d) - Performance curves of cell H103 as a function of temperature at 4.6 and 2.7 mW/cm^2.

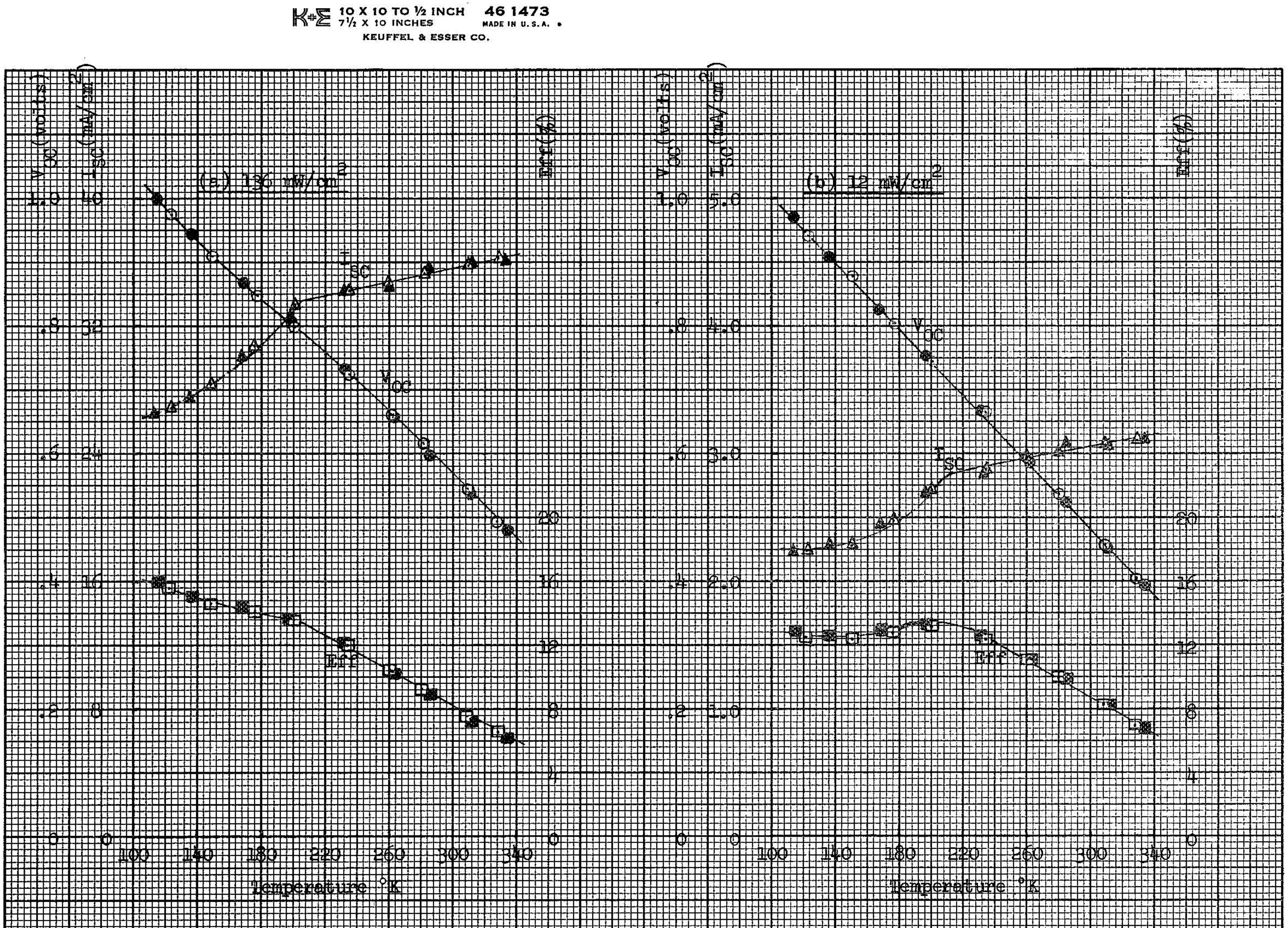

Figure 11(a) & (b) - Performance curves of cell H115 as a function of temperature at 136 and 12 mW/cm^2. Solid data points measured after remounting of cells.

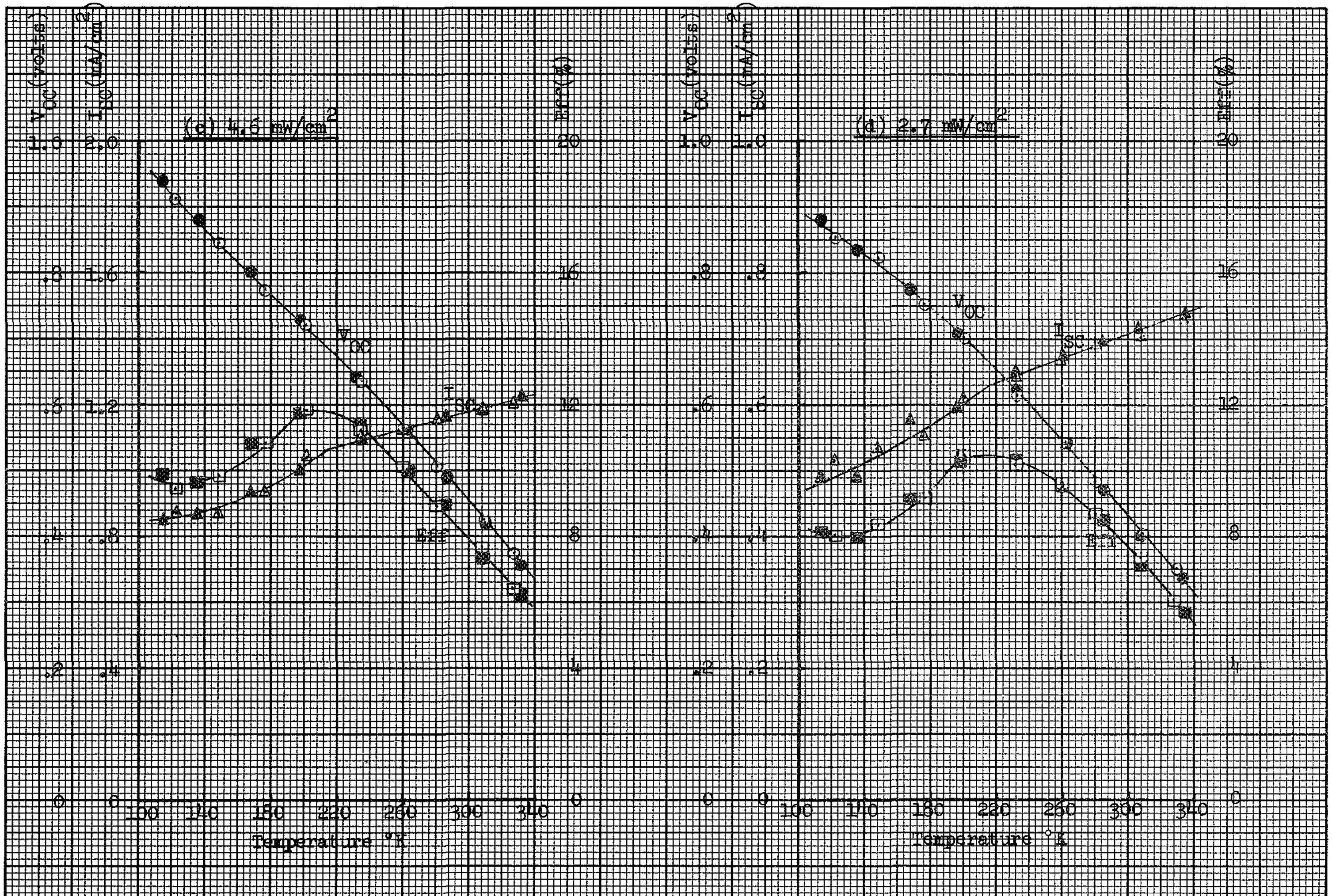

Figure 11(c) & (d) - Performance curves of cell H115 as a function of temperature at 4.6 and 2.7 mW/cm². Solid data points measured after remounting of cells.

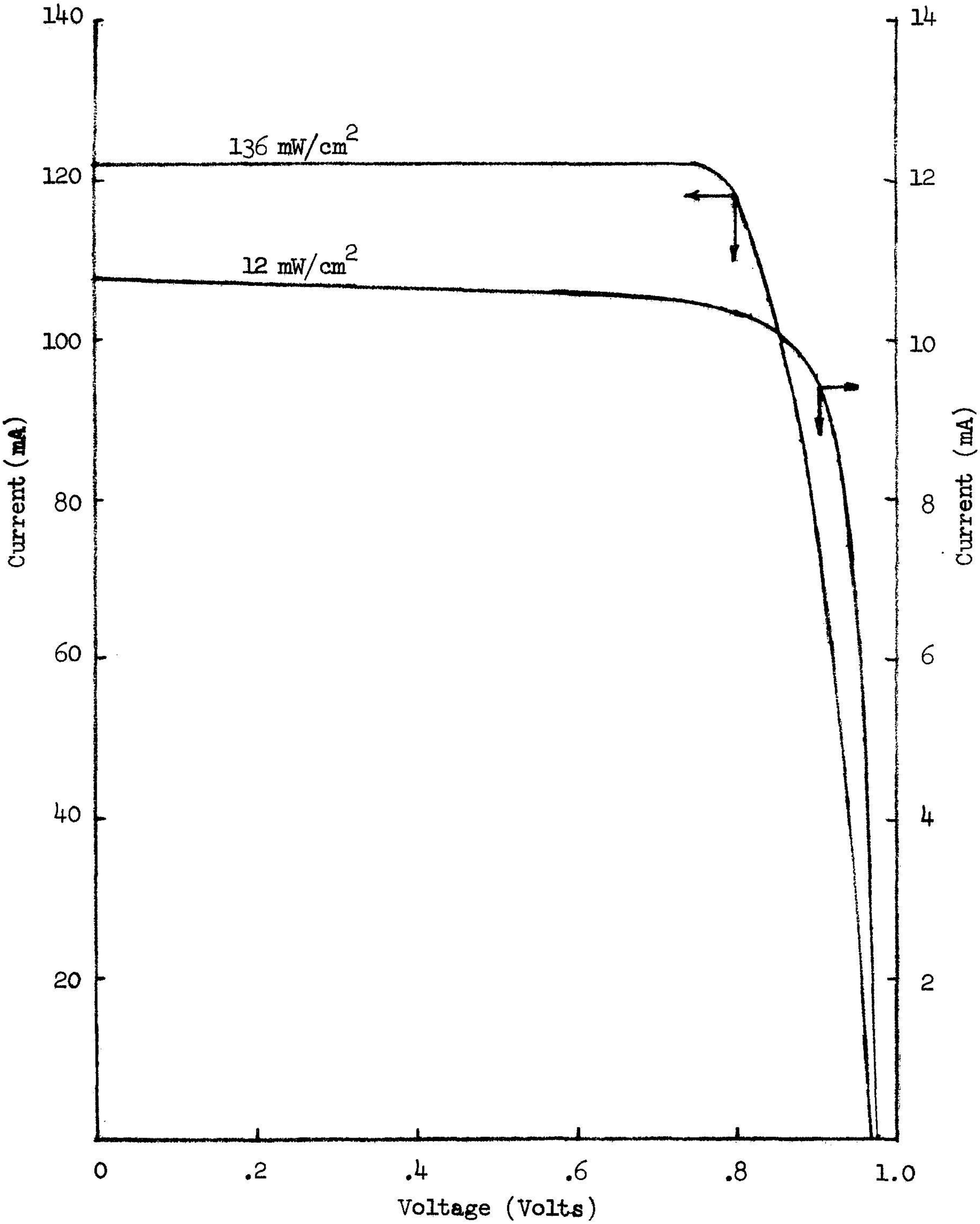

Figure 12 - Current-voltage curve of cell C191 at 116° K at 136 and 12 mW/cm^2

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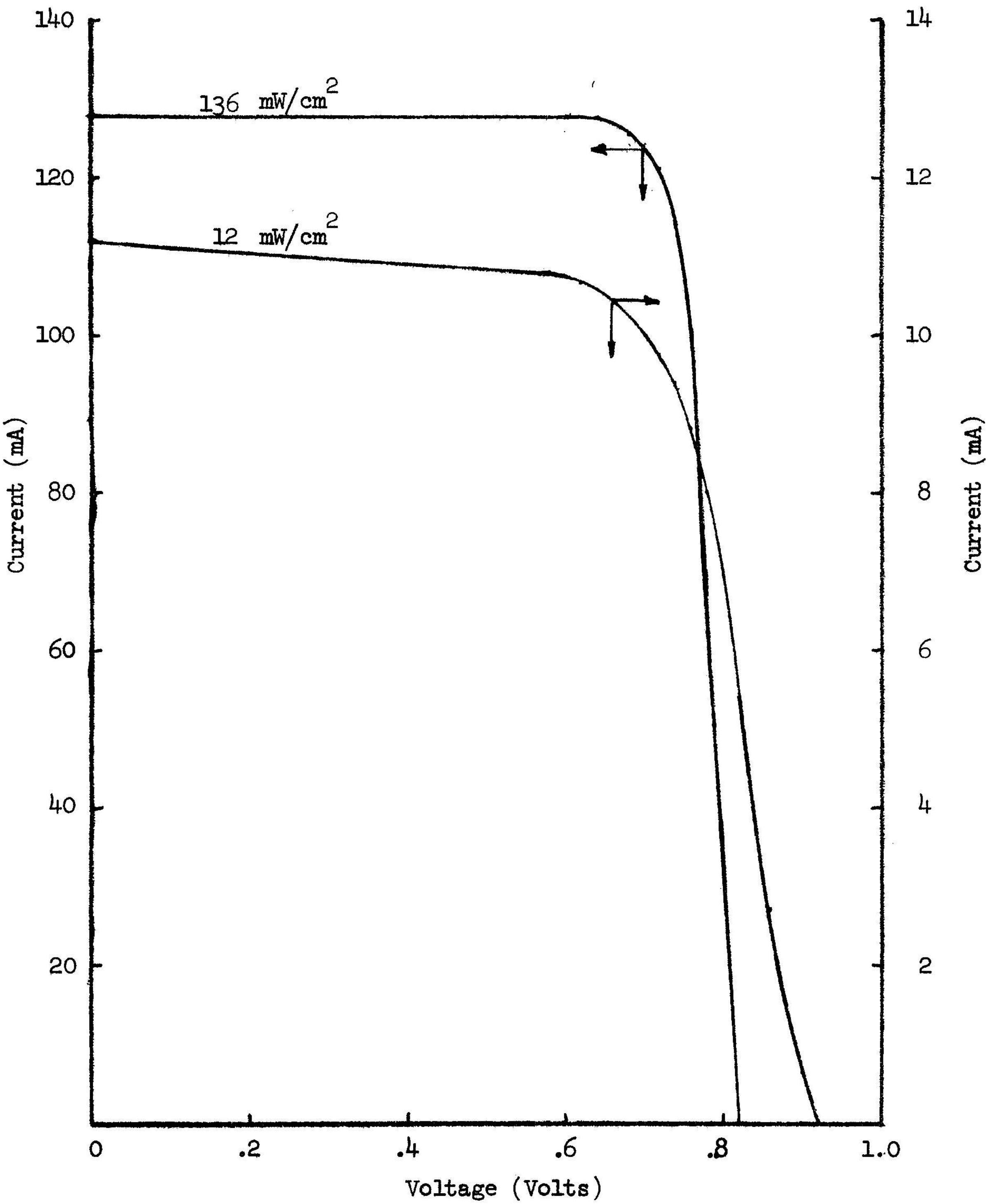

Figure 13 - Current-voltage curve of cell C214 at 114° K at 136 and 12 mW/cm^2

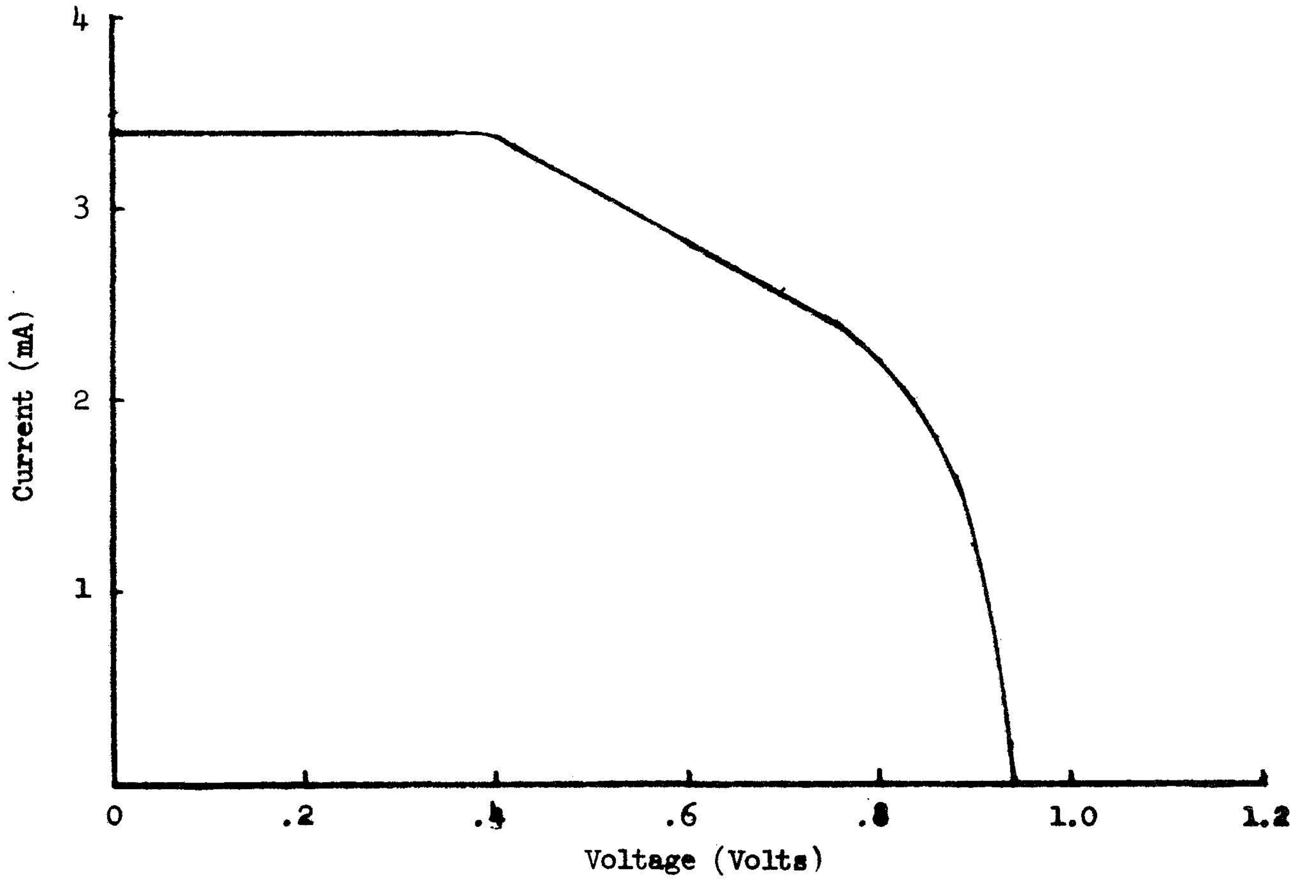

Figure 14 - Current-voltage curve of cell H115 at 114° K and 4.6 mW/cm^2

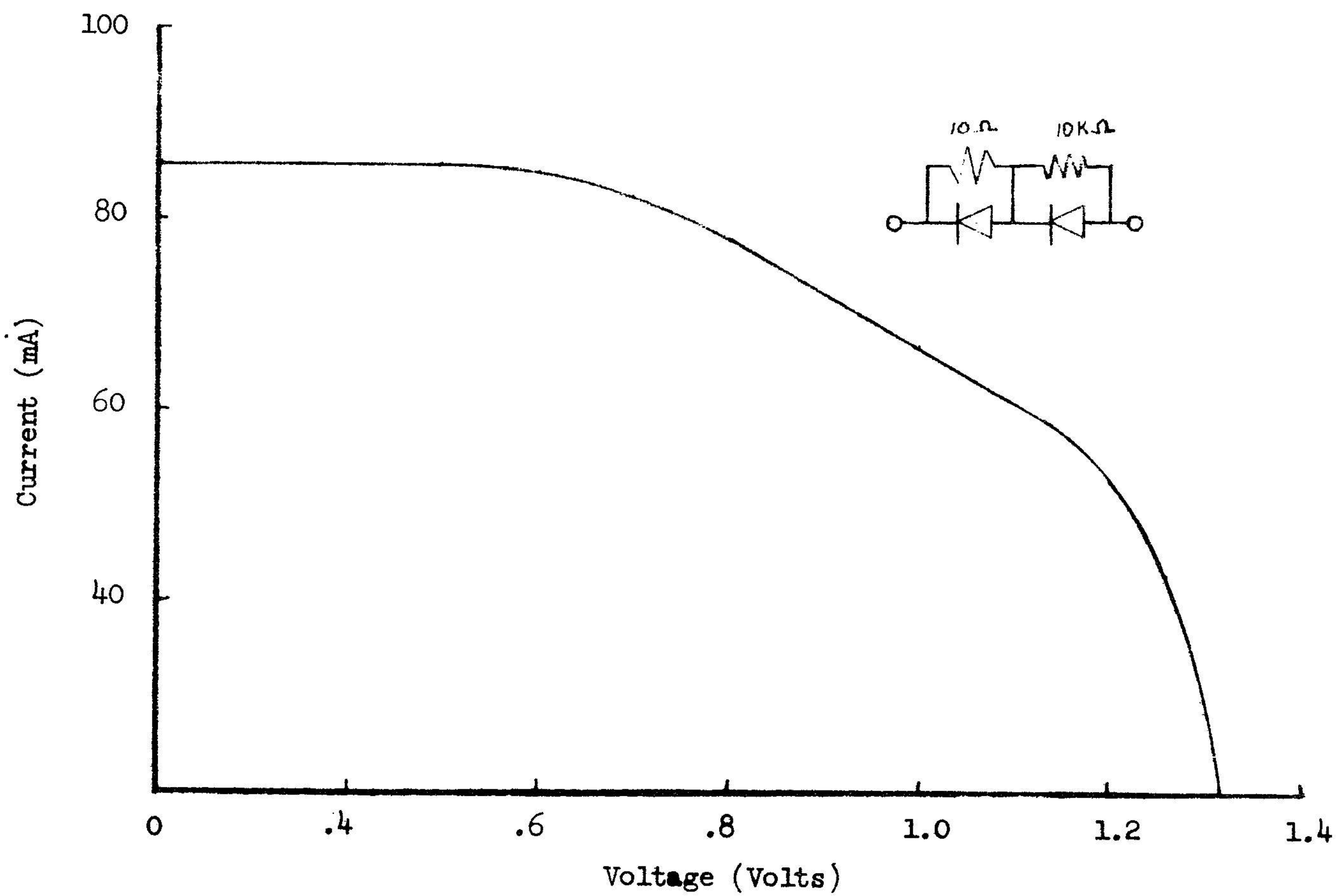

Figure 15 - Current-voltage curve generated by two series-connected silicon cells, one having a 10 ohm shunt resistor; temperature 298° K, illumination intensity about 100 mw/cm^2.